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Research article

Interactive 3D geodesign tool for multidisciplinary wind turbine planning

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ABSTRACT

Wind turbine site planning is a multidisciplinary task comprising of several stakeholder groups from different domains and with different priorities. An information system capable of integrating the knowledge on the multiple aspects of a wind turbine plays a crucial role on providing a common picture to the involved groups. In this study, we have developed an interactive and intuitive 3D system (Falcon) for planning wind turbine locations. This system supports iterative design loops (wind turbine configurations), based on the emerging field of geodesign. The integration of GIS, game engine and the analytical models has resulted in an interactive platform with real-time feedback on the multiple wind turbine aspects which performs efficiently for different use cases and different environmental settings. The implementation of tiling techniques and open standard web services support flexible and on-the-fly loading and querying of different (massive) geospatial elements from different resources. This boosts data accessibility and interoperability that are of high importance in a multidisciplinary process. The incorporation of the analytical models in Falcon makes this system independent from external tools for different environmental impacts estimations and results in a unified platform for performing different environmental analysis in every stage of the scenario design. Game engine techniques, such as collision detection, are applied in Falcon for the real-time implementation of different environmental models (e.g. noise and visibility). The interactivity and real-time performance of Falcon in any location in the whole country assist the stakeholders in the seamless exploration of various scenarios and their resulting environmental effects and provides a scope for an interwoven discussion process. The flexible architecture of the system enables the effortless application of Falcon in other countries, conditional to input data availability. The embedded open web standards in Falcon results in a smooth integration of different input data which are increasingly available online and through standardized access mechanisms.

1. Introduction

Wind energy, as a rich energy source in the Netherlands, has been applied for hundreds of years through wind mills and recently through wind turbines. Aligned with the *EU climate and energy package*, the EU aims to achieve a 20% share of energy from renewable energy sources (2020 climate & energy package, 2009), the on-shore wind power of the Netherlands is intended to increase to 6000 MW in 2020, forming 11 national wind parks (Ontwerp-structuurvisie Windenergie op land, 2013).

Wind turbine site suitability depends on environmental, technological, economic, social and political aspects (Mekonnen and Gorsevski, 2015), making it a complicated decision process for which multiple criteria should be taken into account (Grassi et al., 2012; Tegou et al., 2010). While developers are mainly concerned about economic issues as acquisition, development and operation costs (Grassi et al., 2012; Dvorak et al., 2010), residents and local communities struggle with the environmental externalities, especially noise, shadow flicker and aesthetic influences (Righter, 1996; Swofford and Slattery, 2010; Warren et al., 2005; Aydin et al., 2010; Devine-Wright, 2005; Harding et al., 2008). In spite of large public acceptance (Toke, 2002; Firestone and Kempton, 2007; Mulvaney et al., 2013), these negative impacts result in the resistance of local communities against employing a wind turbine in their

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neighborhood (Jones and Eiser, 2010; Jobert et al., 2007). Such conflicts can lead to the wind turbine project delay or even complete cancellation (Agterbosch et al., 2009; Mari et al., 2011) which are problematic for attaining the national wind energy target.

Research has shown that carefully considering public participation in projects reduces the citizens' oppositions and smooths public acceptance (Khan, 2003; Strachan and Lal, 2004; Aitken, 2010). Wolsink (2007) emphasized the statement of Pasqualetti and Energy (2002) for the Netherlands, that the success of the wind power depends on the public's participation both in information distribution concerning wind power as well as the public's contribution in debates and decisions regarding wind turbines locations. A transparent flow of information to the local citizens from the starting phase of a wind power project and their involvement in the planning process increases their acceptance (Maillebouis, 2003). Therefore, a participatory planning system, which can present the multi-aspect information of a wind turbine site planning, can be of great benefit.

GIS[1] as a system capable of managing geospatial data from acquisition and storage to analysis and presentation (Longley et al., 2001), has been a popular approach in many environmental planning and land allocation decision processes (Malczewski, 1996; Thomas, 2002; Arampatzis et al., 2004; Chang et al., 1997), as there are many geospatial components in such an analysis. In the case of wind turbine planning, there have been several researches on GIS-based assessments and decision support systems on wind turbine impact analysis and site allocation (Mekonnen and Gorsevski, 2015; Aydin et al., 2010; Mari et al., 2011; Ramírez-Rosado et al., 2008; Nobre et al., 2009; Malczewski, 1996; Rodman and Meentemeyer, 2006; Ouammi et al., 2012; Gorsevski et al., 2013; Minelli et al., 2014; Lejeune and Feltz, 2008; Janke, 2010; Simao et al., 2009) verifying the potency of GIS in such decision processes.

The final location of a wind turbine should be usually negotiated among the different participants of the planning process with different, and sometimes conflicting interests. This makes wind turbine site planning a multi-agent decision making process, which should be applied in a multi-criteria planning tool (Ramírez-Rosado et al., 2008; Mari et al., 2011). Such a tool should be an interface between all the components of a participatory plan process from the problem definition to the design, the evaluation and the final decision, introducing geodesign as a proper underlying method for the tool (Warren-Kretzschmar et al., 2012). Geodesign is defined as the set of techniques for planning built and natural environments in an integrated process where the creativity of the design is integrated with impact models of the science (Flaxman, 2010; Dias et al., 2013). Within this iterative framework participants receive feedback during each design step rather than a final feedback when much effort and time have been spent. Iterating through these steps and receiving real-time feedbacks on each step, the final design will be developed more efficiently (Warren-Kretzschmar et al., 2012; Flaxman, 2010). This is a suitable framework for different participatory planning processes, for instance landscape planning, wherein the planners stimulate and evaluate different future landscape settings in the form of scenarios. A geodesign approach which enables the rapid formation, alteration and evaluation of such alternative scenarios improves the participation of the involved parties in the planning process (Albert and Vargas-Moreno, 2012). To make this framework beneficial in practice, new tools for the agile generation and evaluation of design concepts are required (Flaxman, 2010) in which complex analysis can be handled quickly (Warren-Kretzschmar et al., 2012).

[1] Geographical Information System.

In this study we have developed an interactive system to implement the geodesign framework for wind turbine site selection. This system, called “Falcon 3D Geodesign Tool” (will be called Falcon throughout the paper), is developed upon a game engine to conduct the fast interactions required for real-time feedbacks of the geodesign process. This system is an extension to the currently developed Falcon for wind turbine site planning, focusing on the noise (Rafiee et al., 2017) which is now further developed to a multidisciplinary geodesign platform. State-of–the-art GIS techniques have been applied in this tool for serving and querying massive 2D/3D nationwide data. This is in line with the “big data era” which supports performing the geodesign practice at multiple scales (Li and Milburn, 2016). We have implemented complex environmental models into this tool for the impact estimation of wind turbines on the built-up areas as well as the turbine generated power.

2. Methodology: geodesign-based system architecture

Though the outline of a specific geodesign study is formed by the planning participants, a general geodesign framework is posed by Carl Steinitz (1990) (Steinitz, 1990, 2012). This framework comprises six models which will be reviewed at least three times during the geodesign process (Steinitz, 2012). Each geodesign step is implemented separately in Falcon and yet form an integrated decision supporting system. Every step might consist of several modules which can have inter-relations or be independent from each other. Following is a more detailed explanation on the models presented in Steinitz framework and their contributions to our developed system.

2.1. Representation models

Representation models define how the study area should be described in content, space and time (Steinitz, 2014), in which data collection and presentation form the core.

In this study, we have developed a digital platform for the geodesign process within which we have used various techniques to serve large datasets and support real-time interactions. These datasets can be visualized in the 2D or 3D representation modes. Users can be directed to a specific location by typing an address, or navigate manually through view pan, zoom and rotate functionality.

While 2D representation is a familiar and preferred environment for some participants, 3D representations provide the scope for a more intuitive perception of the scenes which equips the user with an easier link between the information and reality (Al-Kodmany, 2002; Dias et al., 2003). Furthermore, this representation is in line with the 3D nature of the different [wind turbine] impact models, such as noise, shadow and visibility.

Representation models are presented to the geodesign team through Falcon platform. The architecture of this platform, concerning only representation models, is depicted in Fig. 1.

The main features of this architecture are explained as follows:

- *Web-based platform*

A web-based system has several advantages over traditional stand-alone systems, among which are the cross-platform capability, easier update deployment and maintenance (db net Solutions, 2007). Assimilation of representation models into a web-based system supports the provision of the common picture of the study area to different users from different locations and platforms.

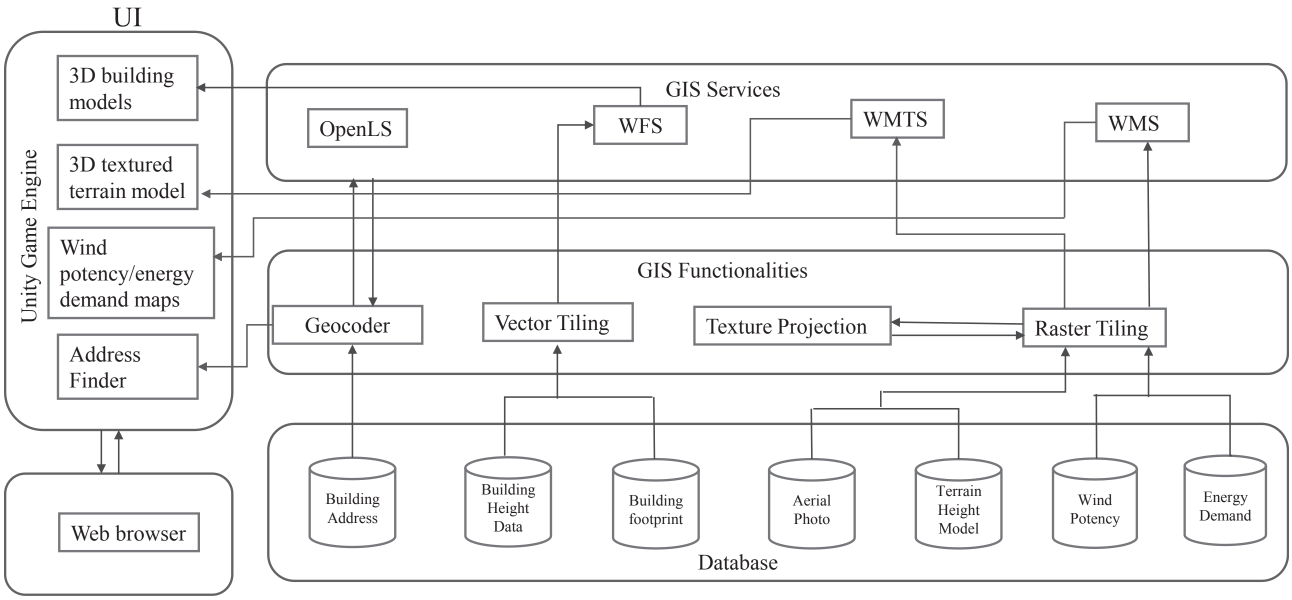

Fig. 1. Architecture of the representation models.

- *Game Engine*

Game engines provide an interactive platform for the navigation in spatial environment depicted through graphical presentation. Different graphical and geometrical optimization techniques support a graphically rich presentation of a spatial environment in different levels of detail (Freudenberg et al., 2001). A game engine often consists out of three main components, namely, a 3D engine, behavior and a network component. While the *3D engine* is responsible for real-time rendering and generation of a constant frame rate for animation, *behavior* is a set of rules for i.a. dynamic simulations and collision detection and *network* assists in multi-player interactions (Freudenberg et al., 2001).

- *Integration of GIS into a game engine*

Integration of geospatial data and GIS functionalities into the interactive environment of a game engine provides the scope for optimized visualization of various georeferenced data, efficient interaction with the data and performing real-time environmental analysis. However, scale is an important issue when geospatial data are involved. While a particular functionality performs well in a neighborhood level, it might not perform the same at regional or national level/at neighborhood level. In larger scales, [massive] geospatial data cannot be handled through traditional data processing systems. Tiling is a technique used to serve large geospatial data in small parts to client. WMS,[2] WMTS[3] and WFS,[4] as OGC[5] standard protocols, are integrated in our platform to serve the raster and vector information of each tile through internet, respectively. In addition to the feasibility of serving large datasets, implementing these standard protocols support the data interoperability through which data from different resources can be served into the platform without any preceding preparations. Geocoder functionality, which is built through the incorporation of OpenLS[6] service, provides the possibility of navigating to a specific address, is a useful component for a system which operates on a national level.

Integration of GIS techniques and the standard protocols into the game engine enabled us to serve large geospatial data of the whole of the Netherlands from different resources into the interactive environment where optimized visualization and various interactions are its two key features (Rafiee et al., 2017).

- *Data*

The study area is described by the 2.5D terrain model which is textured through the aerial photo of the region as well as the extruded 3D building models. 2.5D terrain model and 3D building models are generated using detailed height model of the Netherlands (AHN2[7]) using LIDAR[8] technique. The accuracy of this dataset is 5 cm in both horizontal and vertical planes and the density of the dataset is 6–10 points per square meters (Van der Zon, 2013). The terrain and building models are served into the game engine using 3D vector tiling and the aerial photo is served using raster tiling techniques.

Electricity demand map on the neighborhood level (generated through combining the yearly average electricity consumption data[9] and postcode 6 digits boundary map of the Netherlands) as well as the wind potency map of the Netherlands at 100 m height (SenterNovem, 2005)[10] are served as WMS in Falcon. The former provides an indication of the suitable areas for wind turbine positioning when a local energy supply/consumption target is aimed and the latter provides a useful overview on the proper locations for wind turbines from wind power harvest perspective. The input

[2] Web Map Service.
[3] Web Map Tile Service.
[4] Web Feature Service.
[5] Open Geospatial Consortium (http://www.opengeospatial.org/).
[6] [OpenGIS®] Open Location Service.

[7] AHN2 was collected and made available by the Dutch Water Boards and Rijkswaterstaat, part of the Ministry of Infrastructure and the Environment (http://www.ahn.nl/).
[8] Light Detection And Ranging.
[9] This dataset has been provided as open data through grid operator Liander (https://www.liander.nl/over-liander/innovatie/open-data/data).
[10] This map has been developed by KEMA Nederland B. V. under the assignment of SenterNovem (a former agency of the Ministry of Economic Affairs).

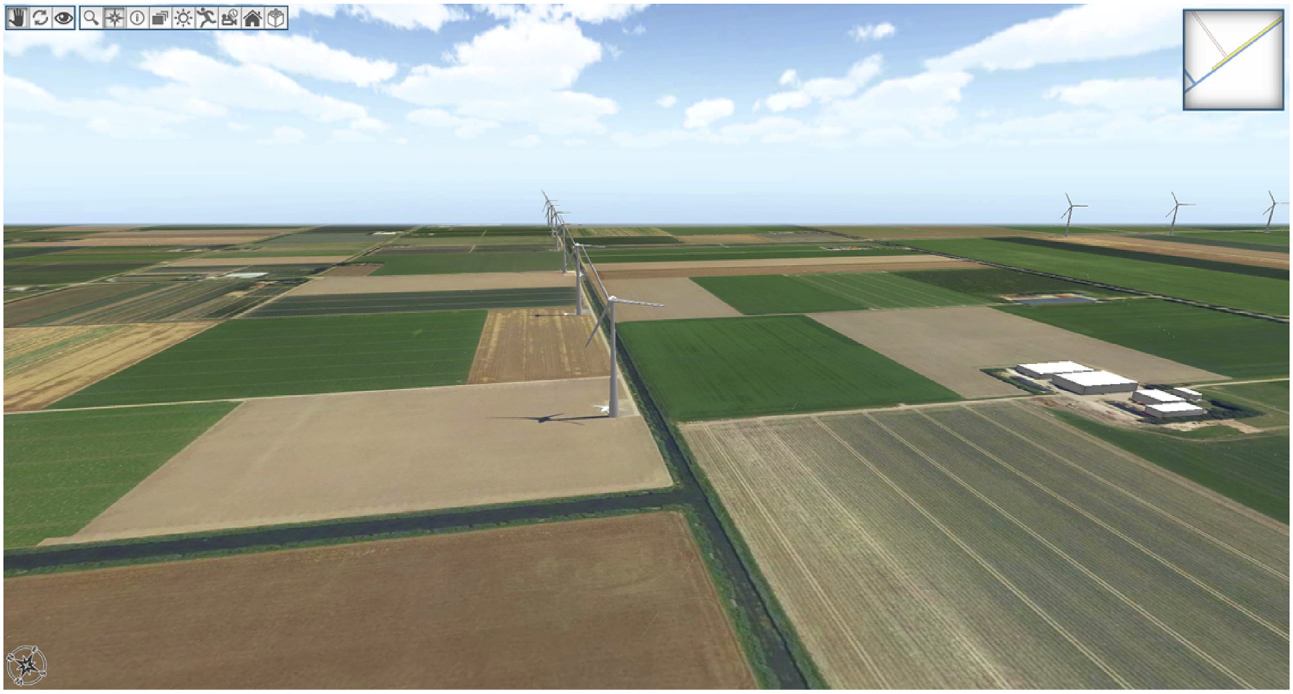

Fig. 2. Existing wind turbines.

data of the wind potency computations are the long-term statistic of wind speeds at KNMI[11] stations and the hourly wind speed at KNMI stations within one year are used for the wind turbine power estimations (see Section 2.5.1).

2.2. Process models

Process models attempt to seek how the study area operates and find out the functional and structural relationships among the elements as well as their interaction behavior (Steinitz, 2014; Reynolds, 2014). These models determine the scope of the project and indicate what should be included (Steinitz, 2012).

The location of exiting wind turbines in the study area influences the positing of new wind turbines in the region due to different factors such as energy distribution and wind turbulence caused by the wind turbines. In this study, we have integrated the location and characteristics of the existing wind turbines of the whole of the Netherlands in Falcon. For presenting the existing wind turbines a standard 3D wind turbine model has been chosen and scaled for each turbine based on its geometrical characteristics obtained from the wind turbine dataset. Fig. 2 presents an instance of existing wind turbines.

One of the affecting issues on the wind turbine locations are the regulations posed by the national and/or local government regarding the wind turbine positioning. These regulations should be identified in the process models (Steinitz, 2012).

In this study we have used the Dutch national rules extracting from Risk Zoning Wind Turbines Manual[12] (Faasen et al., 2013). This document is set up by DNV GL[13] and commissioned by Netherlands Enterprise Agency[14] and provides the uniform method for the quantitative risk analysis of wind turbine operation on the environment and tests the results against the acceptance criteria. This results in the estimated risk distance around buildings, roads, railways, power line, pipeline, primary dike and water.

The risk distance criteria depends on the wind turbine capacity, hub height and rotor diameter. Therefore different distance criteria should be applied for different wind turbines. In this study we have defined the distance criteria for all the wind turbine types in Falcon library and subsequently generated constrained areas' map for each wind turbine type through applying spatial buffers around the aforementioned objects (e.g. buildings). The generated restricted area map is served as WMS in Falcon.

Fig. 3 presents the generated map of the restricted area for two wind turbines. The first one is a 800 kW wind turbine with 50 m hub height and 48 m rotor diameter and the second one is a 4200 kW wind turbine with 135 m hub height and 127 m rotor diameter.

In addition to the visualization, the generated regulation web map services are used as inputs in the *Regulation Control* module for an automated real-time regulation conformity control. Upon placing a new wind turbine or moving it in the game scene, the relevant regulation map will be defined automatically based on the wind turbine type and its relevant WMS layer will be queried. Subsequently, the land allowance status for the wind turbine location will be queried using GetFeatureInfo Request and presented by the interface. The mentioned national regulations are applied in this system for the generation of the restricted area and does not contribute in other decision support processes. Fig. 4 shows the implemented process models.

2.3. Evaluation models

Evaluation models consist of objective or subjective evaluation approaches and criteria to assess the performance of the current situation of the study area. Local inhabitants and stakeholders consider different performance components to evaluate the appropriateness of the current situation. Attractiveness,

[11] the Royal Dutch Meteorological Institution.
[12] Handboek Risicozonering Windturbines.
[13] https://www.dnvgl.nl/.
[14] Rijksdienst voor Ondernemend Nederland.

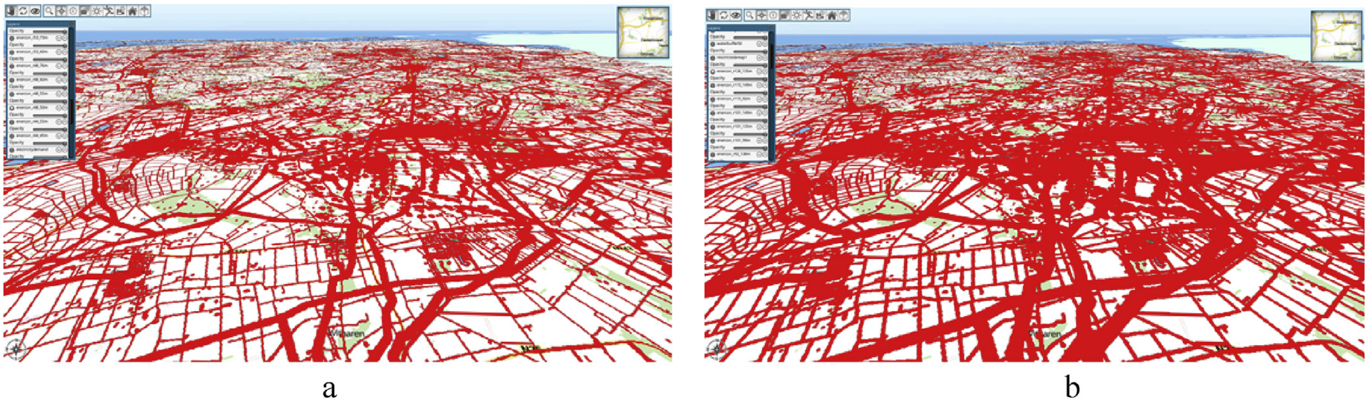

Fig. 3. Restricted area map for a) 48R-50 H wind turbine and b) 127R-135 H wind turbine. The buffer radii are the distance criteria derived from the regulations (Tables 1 and 2) which are dependent on the wind turbine capacity, hub height and rotor diameter.

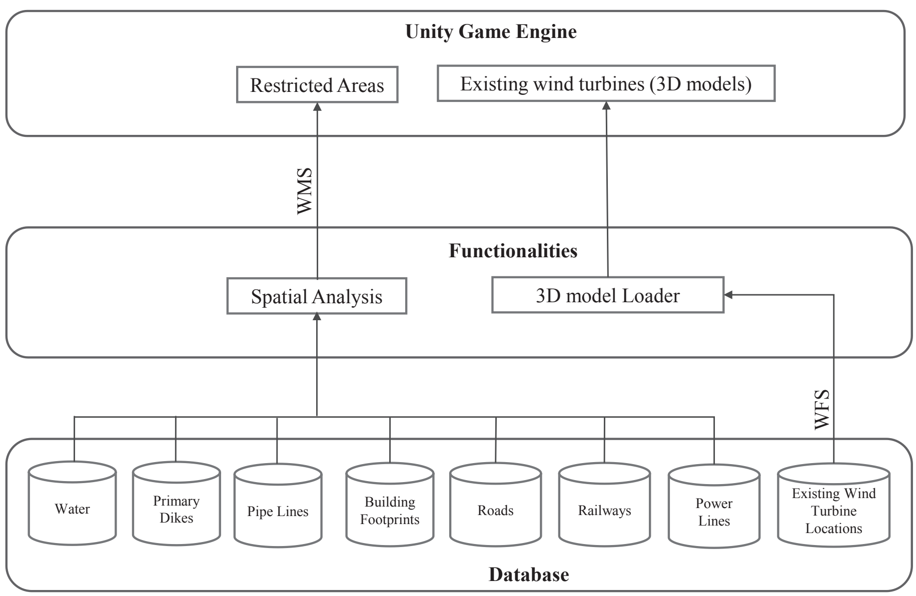

Fig. 4. Process models.

vulnerabilities, existing risks and poor performances of the area are clarified in this step which defines what should be changed and what should be preserved. Therefore evaluation models have great influence on the decision-making process (Campagna and Di Cesare, 2014).

The location and distribution of the existing wind turbines and their total generated power, when compared with the target power (the total desired power for the region), provides an initial outline to the planning group about the proper number, location and specifications of new wind turbines.

National and local regulations on wind turbine locations also play important role on the evaluation of the current situation of the study area. When the location of an existing wind turbine is in conflict with the regulations, e.g. due to wind turbine construction prior to a specific legislation, an orientation towards relocating and replacing it with a new and more efficient wind turbine might arise. Fig. 5 presents the components of the evaluation model.

2.4. Change models

Change models peruse how the study area might be altered through posing different scenario's and alternatives (Steinitz, 2014; Nedkov et al., 2014) which form the first step of a concrete design (Campagna and Di Cesare, 2014). These changes can be propounded by citizens, designers or local authorities (Nedkov et al., 2014). An interactive and collaborative design platform supports a multi-disciplinary planning process in which various participants from different domains can work together.

Altering the amount of the generating power from the wind turbines requires the increase/reduction of the number of wind turbines or replacing the old turbines with new ones. Planning for such an alternation requires the knowledge about the landscape and cannot be performed irrespective of the characteristics of the study area. Therefore the design platform should contain the information of the landscape. An interactive design environment in which the information from different domains is integrated, plays a great role in a multi-disciplinary planning process. Fast performance of the design platform speeds up the discussion procedure and eases the creation of the different scenarios to converge to the ultimate design. Fig. 6 presents the architecture of this design environment.

This platform contains a library of 3D models of different wind

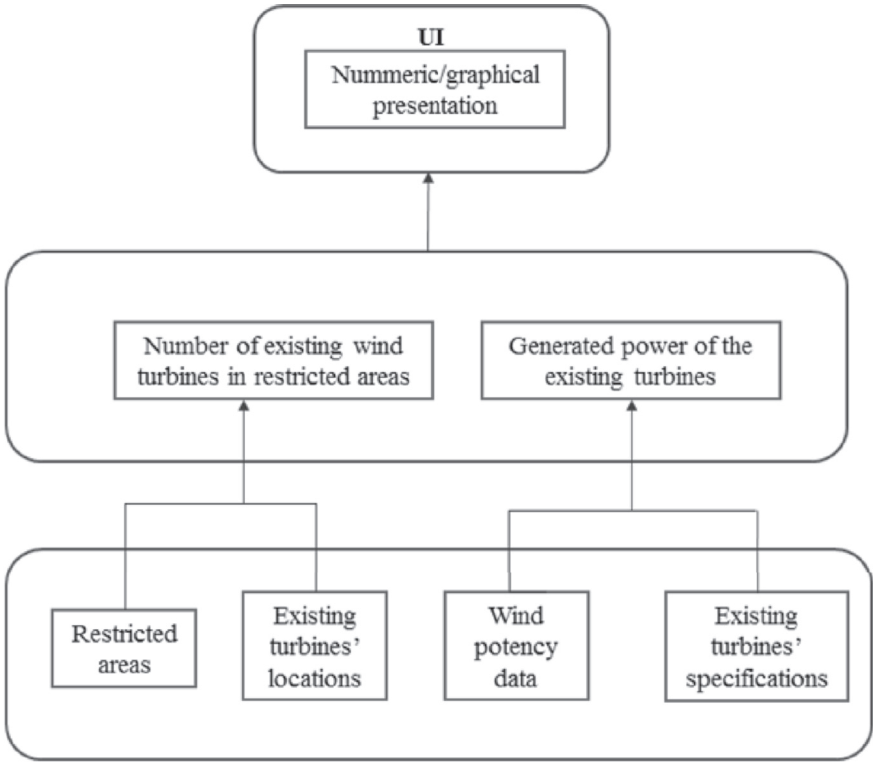

Fig. 5. Components of the evaluation model for the case study.

turbines encompassing their geometric and technical information, delivered by the suppliers. Users can insert different turbines into the design environment through a simple drag and drop act and relocate them with a simple drag and move one (Fig. 7). Once a wind turbine is added to the scene, different technical information of the turbine is presented to the user (Rafiee et al., 2017). Geometric information (e.g. wind turbine hub height and rotor diameter) and other technical specifications (e.g. wind turbine power capacity and sound power level) will be further used in impact analysis step in which both visual and numerical feedbacks are provided to the designers.

2.5. Impact models

A design cannot be finalized regardless of its nearby environment. Each time a scenario is designed, its impact on the environment should be assessed. Likewise, the impact of the existing elements of the environment on the design might be considerable. Therefore, a new design should be evaluated within its spatial context and environment.

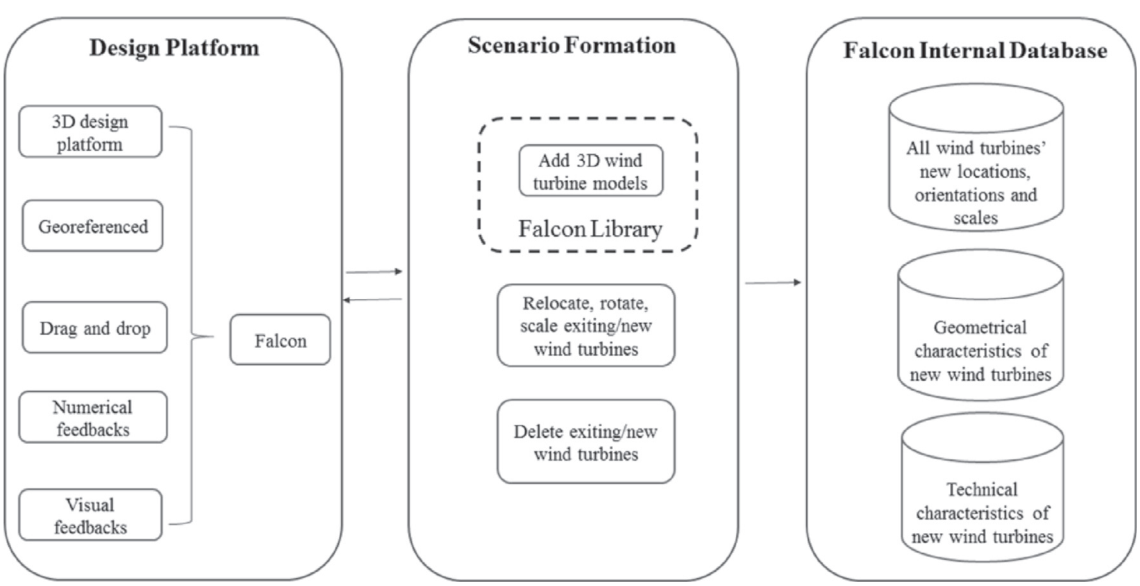

Fig. 6. Architecture of the design platform developed in this study.

Fig. 7. Falcon 3D design platform; designers can add different types of wind turbines into the scene. Once a specific wind turbine is added, its technical information will be queried for further analysis. This information can also be observed by clicking the wind turbine.

Impact models intend to explore the consequences of the alteration proposed by a specific design scenario. The range of the sequels caused by the change might be broad and overlay different domains.

Environmental impacts of a wind turbine can be grouped in two categories of benefits and externalities. The environmental benefits of a wind turbine include the replacement of fossil energy with a clean renewable energy source which leads to CO_2 reduction and the global warming mitigation. The negative externalities of a wind turbine, as the second environmental impact group, comprises of wind turbine noise, shadow and aesthetic impacts, which are, as mentioned in Section 1, the main concerns of local communities and citizens rather than developers. The environmental impacts of a wind turbine depend on the wind turbine specifications, as well as the configuration of the built-up area.

We have implemented analytical models in the 3D design environment of Falcon to present the consequences of a design scenario to the geodesign team. These consequences comprise of wind turbine generated power and the negative environmental impacts which are quantified through sound, shadow and visibility models. Fig. 8 presents the applied impact models in Falcon 3D geodesign tool. Upon the placement of a wind turbine in a specific location, all these impacts are calculated real-time and presented to the team both numerically, as well as visually, by using variant colors and charts.

Table 1 Presents the constituent modules for these impact models as well as the applied technique types and domains and the employed data. Once a new configuration is designed, the different impacts of the design are evaluated real-time through the embedded models of our geodesign environment.

2.5.1. Power generation

In accordance with Justus et al. (1976), the average generated wind power of a wind turbine $\overline{P}_T$ can be estimated as follows:

$$\overline{P}_T = \int_{-\infty}^{\infty} P_T(u) f(u) \mathrm{d}u \tag{1}$$

Here, $P_T(u)$ is the generated power as a function of the wind velocity and $f(u)$ the probability density distribution of the wind velocity u. This probability density distribution can reasonably well be described by the Weibull function:

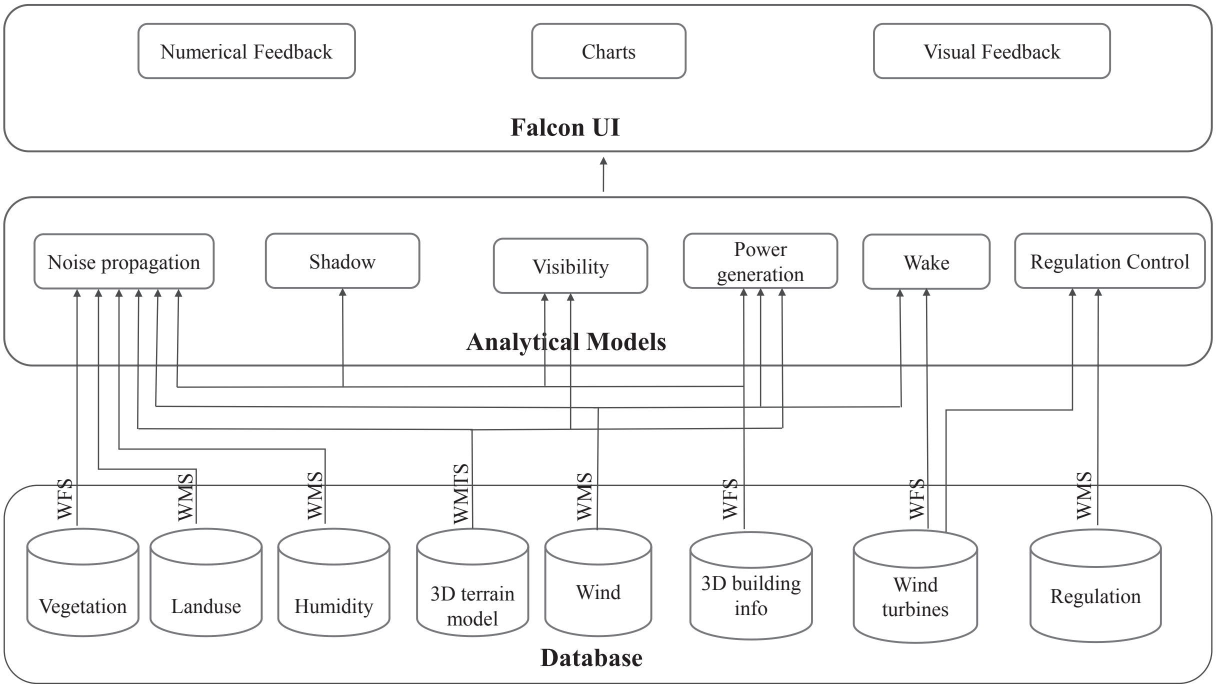

Fig. 8. Components of the impact models applied in this study.

Table 1
Components of the impact model sub-module together with the applied technique types/domains and the employed data.

Module	Technique type	Technique domain	Data
Sound			
Geometrical Spreading	3D Distance	Game engine	3D Building models
			Wind turbine characteristics
Atmospheric Absorption	GetFeatureInfo Request	GIS	Temperature
			Humidity
Vegetation	3D Distance	Game Engine	Landuse
	3D Line Casting	Game Engine	Wind turbine Characteristics
	GetFeature Request	GIS	3D Building models
Ground Reflection	3D Distance	Game Engine	Landuse
			Wind turbine Characteristics
	GetFeatureInfo Request	GIS	3D building models
Turbulence Disturbance	3D Distance	Game Engine	Landuse
	GetFeatureInfo Request	GIS	Wind
			Wind turbine Characteristics
			3D building models
Obstruction	3D Distance	Game Engine	Wind turbine Characteristics
	3D Line casting	Game Engine	3D building models
	3D Collision Detection		
Weather Effects	3D Distance	Game Engine	Wind
			Temperature
	GetFeatureInfo Request	GIS	3D building models
Shadow			
3D Shadow Model Generation	Mesh Filter/Mesh Renderer	Game Engine	Wind turbine geometrical characteristics
Shadow Model Interaction With Buildings	3D Collision Detection	Game Engine	3D building models
	GetFeatureInfo Request	GIS	
Visibility			
Line-of-Sight Analysis	GetFeatureInfo Request	GIS	3D building models
			2.5D terrain model
	3D Collision Detection	Game Engine	Wind turbine geometrical characteristics
Power Generation			
Yearly Average Generated Wind Power	GetFeature Request	GIS	Wind
			2.5D terrain model
			Wind turbine geometrical and technical characteristics
Regulation Control			
Regulations Conflict Control	GetFeatureInfo Request	GIS	Restricted Areas
Wake Control			
Wake Conflict Control	Mesh Filter/Mesh Renderer	Game Engine	Wind turbine geometrical characteristics
	3D Collision Detection	Game Engine	

$$f(u) = \frac{k}{a}\left(\frac{u}{a}\right)^{k-1} e^{-\left(\frac{u}{a}\right)^{k}}. \tag{2}$$

The actual shape of the Weibull function is determined by the scale factor a and the shape factor k, determining the skewness of the distribution. Wieringa and Rijkoort (1983) considered the application of the Weibull distribution for the Dutch wind climate. They found limited variation of the shape factor and suggested values of $k = 1.74 \pm 0.06$ for onshore locations and $k = 2.0$ for coastal areas. The scale factor can be estimated from the mean yearly wind velocity $\overline{U}$. Realistic normalized values for the scale factor in the Netherlands vary from $a = 1.123\overline{U}$ for onshore locations to $a = 1.128\overline{U}$ for coastal areas. These values are normalized to a height $z_0 = 10$ m above open terrain. Once the coefficients a and k are known for this reference height, their values for the desired altitude can easily be determined (Justus et al., 1978).

The power curve is specific to wind turbine characteristic, but in general, the following expression can be adopted (Akpinar and Akpinar, 2005):

$$P_T(u) = \begin{cases} 0 & , \quad \text{for} \quad u \le U_{ci} \\ P_{TR}\dfrac{u^k - U_{ci}^k}{U_R^k - U_{ci}^k} & , \quad \text{for} \quad U_{ci} < u \le U_R \\ P_{TR} & , \quad \text{for} \quad U_R < u \le U_{co} \\ 0 & , \quad \text{for} \quad u > U_{co} \end{cases} \tag{3}$$

In this expression, U_{ci} and U_{co} are the cut-in and cut-out wind velocity of the turbine, respectively, while U_R is the rated wind velocity. P_{TR} represents the generated power at rated wind velocity, and k is the shape factor from the adopted Weibull distribution.

A similar model has been applied in the studies done by Lu et al. (2002) and Celik (2004). The presented model is applicable for flat terrains without too much atmospheric disturbance from buildings and vegetation. The model could be extended to account for the presence of buildings (Kastner-Klein and Rotach, 2004; Grimmond and Oke, 1999; Macdonald et al., 1998) and vegetation (Dellwik et al., 2014), respectively.

The hourly wind data is extracted from KNMI. For each station, we have calculated the mean wind velocity probability density distribution through a Weibull function (Equation (2)). Once a wind turbine is added to the scene, the nearest station to the turbine will be queried and the corresponding wind velocity probability density distribution parameters will be retrieved. Linking the wind turbine characteristics with the wind velocity density distribution, we have determined the mean power production of the wind turbine (Equation (1)).

Since the goal of a wind turbine siting project is to fulfill a target energy amount, in each design stage an overview of the produced and residual power supports the stakeholders with a better orientation on the more proper distribution and characteristics of the remaining wind turbines.

2.5.2. Noise

The noise of a wind turbine, as perceived by a receiver, originates from the combination of the noise generation at the turbine and the noise propagation towards this receiver (Wagner et al., 1996). At the turbine, the noise is generated mechanically or aerodynamically. Several detailed models have been developed for the prediction of this noise (Filios et al., 2007; Oerlemans and Schepers, 2010; Tadamasa and Zangeneh, 2011). As a rule of thumb, the generated noise can be estimated from the rotor diameter and the blade tip speed (Manwell et al., 2002):

$$L_{WA} = 50(\log_{10} V_{tip}) + 10(\log_{10} D) - 4, \tag{4}$$

where L_{WA} is the overall A-weighted sound power level, V_{tip} the blade tip speed and D the diameter of the rotor.

Ray tracing models are commonly applied for the prediction of the propagation of the noise from a single sound source (Lamancusa and Daroux, 1993, Attenborough et al. (1995, 2006), and Prospathopoulos and Voutsinas, 2007). Given the sound pressure level L_{p_0} at unit distance from a source, the sound pressure L_{p_r} at a receiver location can be obtained from:

$$L_{p_r} = L_{p_0} - \sum A_i, \tag{5}$$

where A_i represents the excess attenuation that may result from geometrical spreading, ground reflection, atmospheric turbulence, atmospheric absorption, absorption through vegetation and diffraction.

The attenuation from the geometrical spreading of a single wave can be found from the inverse square law, where the reflection from the ground can be accounted for via the superposition of the direct and the reflected waves (Piercy et al., 1977). This approach accounts for the wave incidence angle, path length for the direct and the reflected waves, the sound frequency and the impedance of both air and ground. For the estimation of the latter, several empirical results relations exist (Delany and Bazley, 1970; Chessell, 1977; Nicolas et al., 1985; Embleton et al., 1983; Attenborough, 1992).

The effect of atmospheric turbulence can be included on the basis of the models from Daigle et al. (1978) and Daigle (1979). These models allow for the estimation of the long-term average of the mean square of the sound pressure, where the effect of different weather conditions is accounted for, through the index of reflexion and a specific turbulence length scale (Johnson et al., 1987).

Atmospheric absorption is caused by sound energy scattering due to viscous losses and relaxation process, and can be expressed in terms of an absorption coefficient. Bass et al. (1990) presented an empirical relation for the absorption coefficient as a function of the sound frequency, the temperature and the humidity. The absorption is shown to be higher for high frequencies, while the absorption generally decreases for increasing humidity. Regarding the dependency on temperature, the absorption coefficient shows a peak at a specific temperature, the value of which increases for increasing frequency and decreasing humidity (Harris, 1966). Attenuation through vegetation results from scattering, reflection and refraction, from leaves and trunks. As an approximation, the attenuation can be calculated from the sound frequency and the crossing distance (Kurze (1971)).

In order to predict the sound level behind an obstruction, such as a building, the diffraction model of Kurze and Anderson (1971) is adopted. This engineering model uses the Fresnel number to estimate the attenuation.

Apart from diffraction, refraction due to the wind and temperature conditions is considered. Both wind and temperature gradients affect the sound wave pattern, potentially resulting in sound shadow zones – areas with a sudden decrease in the sound pressure. Such shadow zones may occur at a certain distance from the source in the upwind direction, as a result of the curvature of the sound wave paths. The distance at which a shadow zone may appear can be predicted with the model described by Wagner et al. (1996). The applied sound models of Falcon are explained in details in Rafiee et al., 2017).

The different sound model components, namely, geometrical spreading, atmospheric absorption, vegetation effect, ground reflection, air turbulence, diffraction due to obstacles and refraction due to shadow zones are implemented in Falcon as separate noise modules which can be presented detachedly in Falcon. The total resulting sound from the turbine on the surrounding buildings, as the integration of all the aforementioned components, is implemented in Falcon geodesign tool (for a detailed explanation see (Rafiee et al., 2017)).

Fig. 9 presents the wind turbine total noise calculation in Falcon. The different noise components, resulting from the turbine noise emission and propagation, are included in this calculation. Upon the placement of a wind turbine in the scene, its sound impacts on the surrounding buildings (within 1 km distance) are calculated and presented real-time both visually (through building colorization and relevant-colored chart) and numerically.

Falcon contains a simplified sound module, next to the above mentioned detailed sound module, which takes only the geometrical spreading (as the major defining component) into account for a faster performance. For the area depicted in Fig. 9, the performance duration of the advanced sound module is around 980 ms versus 10 ms for the simple sound module.

In addition to the sound propagation prediction of the current climatic situation, Falcon provides the possibility for different climatic scenario analyses. This can support the seasonal or extreme climates impact analyses on the propagated sound, for instance. Wind speed, humidity and temperature values can be adjusted through the employed sliders in the interface (Fig. 9). By altering the value of each slider, all the relevant sub-modules are triggered and updated real-time.

2.5.3. Shadow

For the reconstruction of the objects' shadows at a specific moment, the position of the sun, expressed in solar azimuth and altitude should be known. We have calculated the solar azimuth and altitude for a specific time on a specific location based on the orbital algorithms (Vallado, 2001). Once the azimuth and altitude of the sun is known the shadow vertices for each object can be calculated using an affine transformation.

While the instantaneous shadow analysis is helpful for a specific time, stakeholders may also be interested in a broader view on the shadow impact of a wind turbine. They might want to have an insight on the average shadow impact in summer when they sit in their garden or winter when the shadows are longer. Furthermore, different stakeholders have different priorities and purposes based on which a flexible shadow analysis is required. Therefore, in addition to the 3D model reconstruction of the instantaneous shadow, we have implemented the algorithm for real-time reconstruction of the yearly average, seasonal and monthly shadow models. For this purpose, the minimum and maximum solar azimuth and the average of the elevation within a whole year, season and month are calculated through the orbital algorithms and applied in the shadow model, replacing the momentary solar azimuth and altitude.

To spot the affected buildings by the shadow volume of the wind turbine, we have performed the collision detection analysis in Falcon. Beside the visualization possibility, we have implemented the numerical feedback in Falcon, through displaying the total number of affected building by the shadow in the scene. This can orient the geodesign team in an optimized positioning of the wind turbine where less buildings will be influenced by its shadow.

2.5.3.1. Instantaneous shadow. The instantaneous 3D shadow model is generated based on the instantaneous solar azimuth and elevation of the arbitrary time, day, month as well as the wind turbine location and geometry. Fig. 10 presents the wind turbine instantaneous shadow implementation in Falcon. Effected buildings by the turbine's shadow are displayed in black. The total number of affected building are displayed on the top of the image. The shadow slide is shown on the top left of the image. The user can alter the time, day and month values and the 3D shadow model will be constructed real-time.

2.5.3.2. Average shadow. The average shadow sub-module contains yearly, seasonal and monthly average 3D shadow models. Fig. 11 presents the wind turbine average shadow reconstruction in Falcon.

The real-time performance of the wind turbine shadow is depicted in Film 1.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.09.042.

The optimized performance of the game engine in collision

Fig. 9. Wind turbine noise impact calculation in Falcon. The wind turbine noise impact is presented real-time both visually (colorized buildings and chart) and numerically (top). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

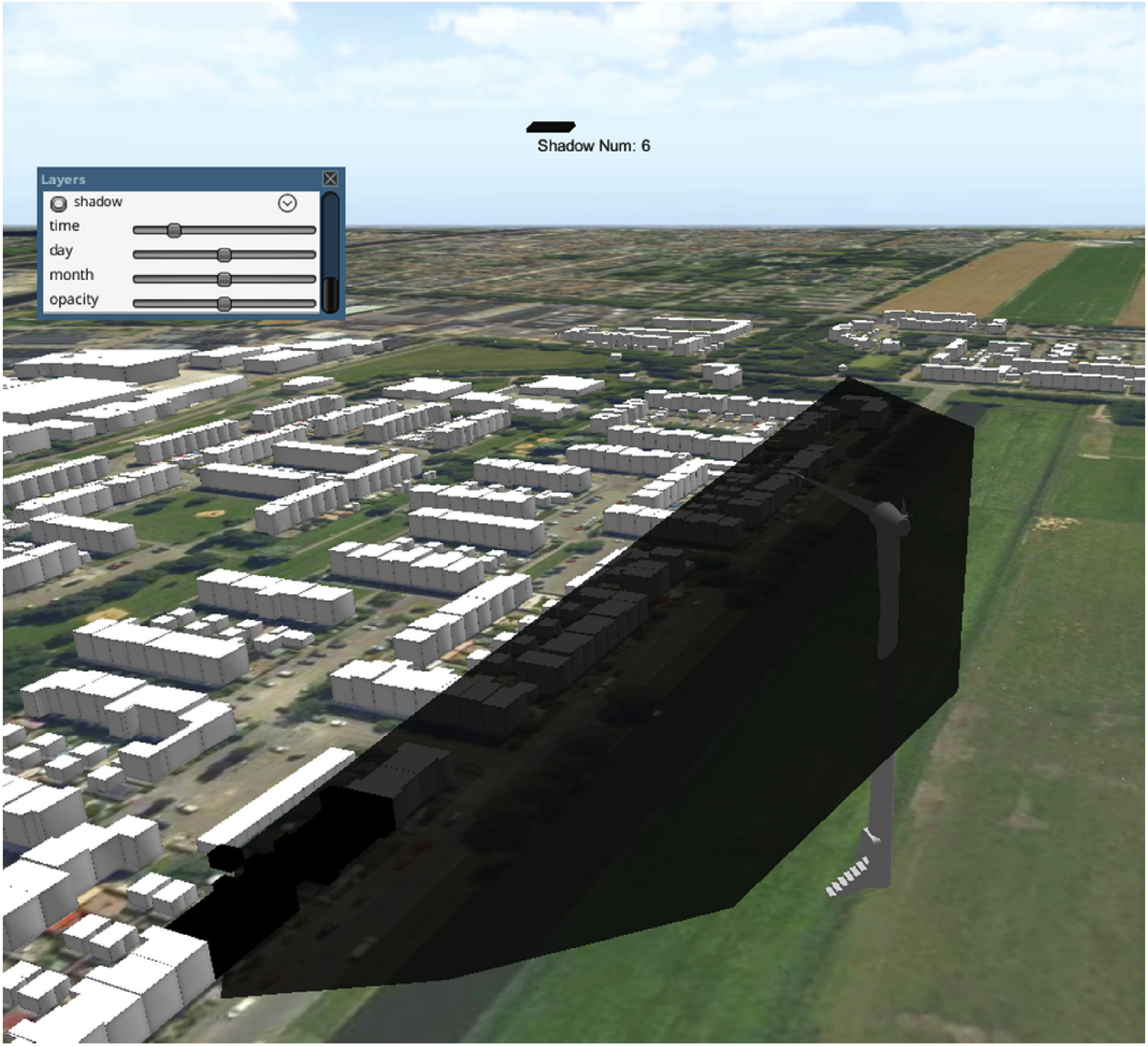

Fig. 10. 3D wind turbine instantaneous shadow model implementation in Falcon. Upon the time/day/month alternation (top left slider) updated shadow model is reconstructed real-time.

detection, together with the implementation of real-time solar calculations and 3D shadow algorithm, resulted in a real-time shadow impact analysis. At the moment, this analysis cannot be implemented real-time in a conventional GIS system, as the intersection operation is a computationally demanding and time-consuming process. On the other hand, loading the georeferenced objects of the whole country into a game engine and the following analysis would be hardly possible without the optimization GIS techniques, such as vector tiling. Therefore, an integration of GIS objects and techniques into a game engine can greatly support interactive and real-time shadow analysis.

2.5.4. Visibility

The wind turbine visibility from each building is estimated through the optimized line casting/collision detection possibility of Falcon, based on Unity game engine. A line of sight is defined between the target point (center point of each building) and the wind turbine hub location and height. Subsequently, the obstruction of the line of sight by other buildings is controlled through the collision detection between the sight line and the surrounding 3D building models. If there are any obstacles colliding the line of sight between the wind turbine and the target point, the wind turbine is considered as "not visible" and otherwise "visible" (Fig. 12).

The agile performance of the wind turbine visibility module is presented in Film 2.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.09.042.

The optimized performance of the game engine on line casting/collision detection speeds up this procedure, which is a computational demanding task and cannot be performed real-time in a conventional GIS system.

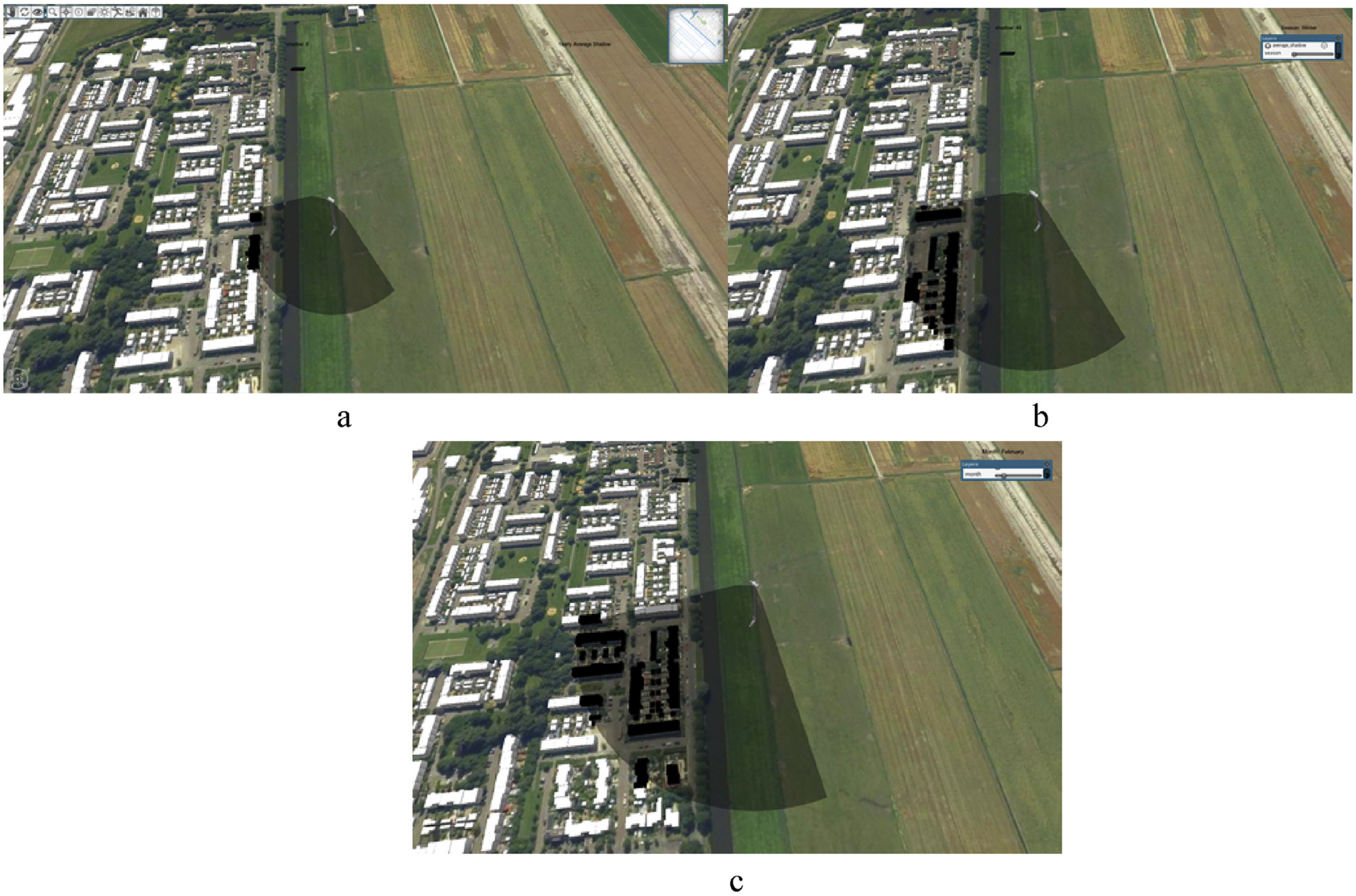

Fig. 11. Wind turbine average shadow a) yearly average, b) seasonal average (winter) and c) monthly average (February).

Fig. 12. Visibility analysis performed in Falcon. The wind turbine is visible from taller buildings whose line of sight is not blocked by other buildings (pink) while not visible from lower buildings hidden behind taller buildings (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.5.5. Wake area

The flow disturbance from wind turbines in the upwind segment of the area, reduces the energy yield of the neighboring wind turbines (Limpo, 2011). To minimize the effect of flow disturbances, a minimum spacing between the wind turbines should be accounted for. In line with previous studies, for an array loss less than 10%, we have applied a spacing of 8–10 and 5–7 times the rotor diameter in the prevailing and crosswind directions, respectively (Lissaman et al., 1982; Manwell et al., 2010). This forms two elliptic areas around a wind turbine, called wake areas, into which no other wind turbines should be placed. The major axis should be chosen towards the prevailing wind direction, which for the Dutch wind climate corresponds with the south-west to north-east direction.

These wake areas around each turbine, are presented in Falcon. Each time a wind turbine is added to the scene, its rotor diameter will be retrieved from the database and its wake ellipses will be constructed, rotated towards the dominant wind direction and displayed real-time in the viewer.

In addition to the visual analysis, the interference between the wake areas of the inserted wind turbines are inspected using the game engine collision detection functionality. Upon the insertion or movement of a wind turbine in the scene, the collision of its inner and outer ellipses with the other wake area ellipses of the scene is detected separately. As a result, the total number of wake area conflicts for the inner and outer ellipses are calculated and presented real-time through the interface. Fig. 13 illustrates the numeric feedback regarding the inner and outer wake area interference of multiple new and existing wind turbines (top right). *Vacant area conflict first ring* attribute depicts the total number of the inner ellipse collisions with each other and *vacant area conflict second ring* attribute presents the total collision numbers between the outer ellipses as well as the inner-outer ones.

2.6. Decision models

The purpose of decision models is to determine the preferences among all the feasible scenario's and alternatives to converge to the final decision. The final decision can be influenced by the local knowledge as well as the design scenario's impacts presented at impact models.

Since in such a decision process several [conflicting] influential criteria and preferences play a role, a multi-criteria decision analysis (MCDA) can help the stakeholders and decision makers in converging to the best alternative. This, alongside the local knowledge of local inhabitants helps the decision team in approaching the final decision.

In this framework, we have applied Weighted Linear Combination (WLC) for defining the decision function. This function is specified as the overall combinatory value in location i defined as $V(A_i)$ in Equation (6).

$$V(A_i) = \sum_{k=1}^{n} w_k v(a_{ik}) \tag{6}$$

where w_k is the assigned weight to the kth criteria, a_{ik} is the value of the kth criteria in location i and v is the value function, which converts the raw criteria values into a standardized one (Malczewski and Rinner, 2015) (Equation (7)).

$$v(a_{ik}) = \left(\frac{a_{ik} - \min\{a_{ik}\}_i}{\max\{a_{ik}\}_i - \min\{a_{ik}\}_i}\right)^{\rho} \tag{7}$$

for the k_{th} criterion intended to be maximized and

$$v(a_{ik}) = \left(\frac{\max\{a_{ik}\}_i - a_{ik}}{\max\{a_{ik}\}_i - \min\{a_{ik}\}_i}\right)^{\rho} \tag{8}$$

for the k_{th} criterion to be minimized. The shape of these functions is determined by ρ (Malczewski and Rinner, 2015).

To estimate the criteria weights (w_k), as the relative importance of a criterion compared to other criteria, we have applied two approaches, namely rating and pairwise comparison methods. Fig. 14 presents our proposed decision model.

3. Results and discussion

This research focuses on the integration of different aspects regarding wind turbine siting. The remaining of this section contains the implementation results of how the different aspects are combined in the system in order to best inform the user. In addition, it contains the discussion on how the system can be potentially applied in an international context.

3.1. Multi-criteria analysis

While each particular wind turbine impact (noise, shadow, visibility and power generation) can be of importance for a specific target group, the additional information on the overall impact of a wind turbine provides a collective indicator for the stakeholders. Therefore, we have integrated all the impact modules into a single component which, upon a wind turbine placement in the scene, calculates and integrates all the wind turbine effects simultaneously. While it is still possible for the stakeholders to choose a single (or multiple arbitrary) impact module(s) for wind turbine influence investigation, the overall impacts offers a better scope for a multi-criteria analysis. The real-time simultaneous performance of the sound (simple), shadow, visibility and power generation is depicted in Film 3.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.09.042.

3.1.1. Scoring

In this implemented multi-criteria analysis, we have defined a decision function which takes wind turbine sound, shadow, visibility and power generation into account (Equation (6)). The [scaled] value of this function, called “score” in this study, is an auxiliary information which can potentially orient the stakeholders towards a more convergent decision.

The applied criteria in the decision function includes the number of buildings receiving above 35 dB(A) noise, the number of buildings affected by the turbine(s)' shadow, the number of buildings which have a view on wind turbine(s) and the amount of the yearly produced power by the turbine(s). The quantity of these criteria is standardized through value functions to be used in the decision function. For all the criteria we have applied a maximizing value function (Equation (7)) so that all the criteria can be added together and the final “score” becomes ascending with the direct relation to the appropriateness of the scenario configuration. The value functions of the decision criteria are considered linear, in line with most of the GIS-MCDA[15] approaches (Malczewski and Rinner, 2015; Malczewski, 2006).

The applied weights of a decision function can have significant impact on its final value. In the case of a planning process consisting of participants with different domains and roles, the preferences of the decision agents with respect to the criteria significance often

[15] GIS-based Multicriteria Decision Analysis.

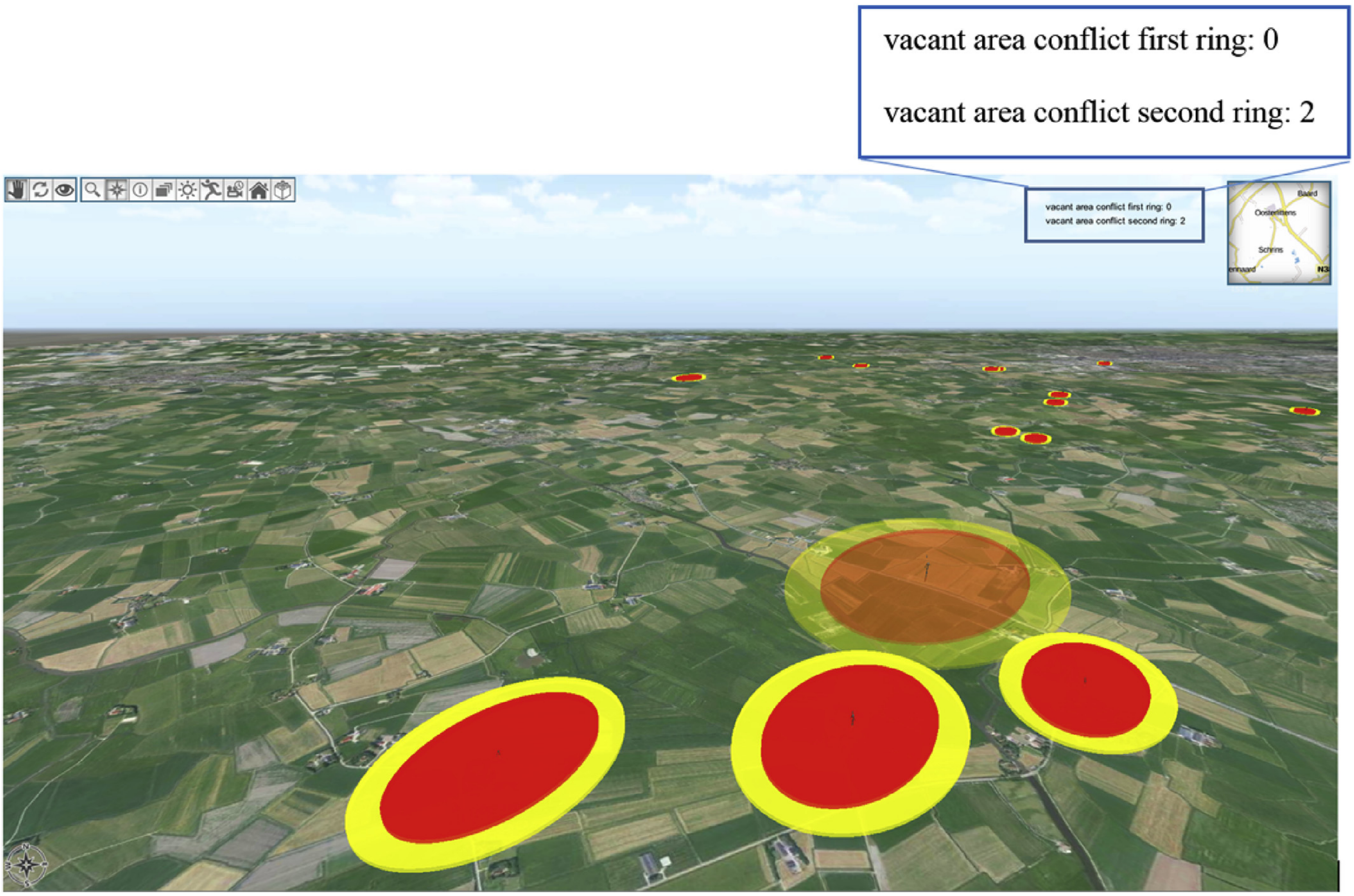

Fig. 13. Numeric feedback regarding the wake area interference between the new (transparent) and existing wind turbines.

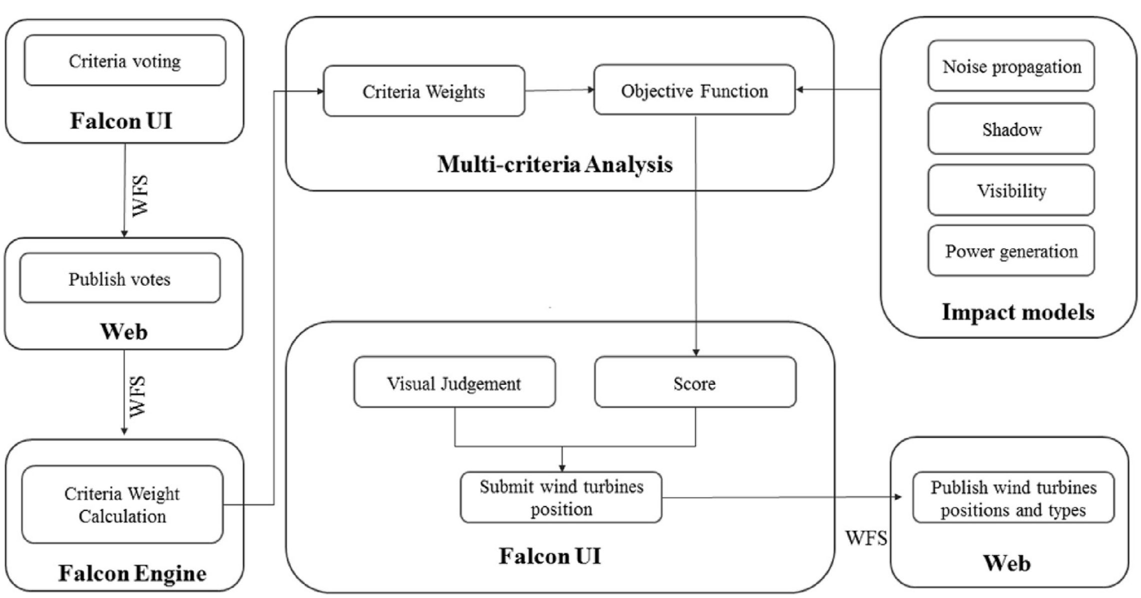

Fig. 14. The applied decision model in Falcon.

differ and conflict. For instance, in the case of wind turbine planning, developers assign more weights on the produced power while local communities might allocate higher weights to the wind turbine sound, shadow and visibility. This conflict of vision on the assigned weights might lead to contradictory *score* values. Therefore it is important that these weights are defined collaboratively by the different participating stakeholders. In our system, there are two ways for collaborative determination of criterion weights of the objective function, namely collective and individual collaboration. The former refers to the case where all the participants use a single device for scenario design whereas in the latter case, stakeholders are participating through individual devices. Two weighting methods, namely, Rating and Pairwise Comparison are implemented in Falcon (see Section 2.6), which can be used separately or for the comparison of the resulting scores.

In a collective process, the weight for each criteria can be discussed among the stakeholders in person and will be assigned to the objective function through Falcon *weight sliders*. Each time the weight of a criteria is altered by a user through its slider, the weights of the other criterion, in the Rating method, will be updated automatically and are displayed seamlessly through their sliders. The added/subtracted value for the other criterion equals to one third of the difference between the old and new value for the altered criteria so that the total summation of the weights remains equal to 1. For an individual collaboration process, we have developed a voting system where each participant can vote for the criteria weights. Voting is a reliable approach in supporting a group decision making (Laukkanen et al., 2002). In our system, this is performed by defining weights through *weight sliders* and submitting them to the system. Each submitted vote will be sent to the server and added to an existing web feature service, which holds the voted weights of all other participants. For each criteria, the average of all weights are then calculated and applied in the decision function (as implemented by Laukkanen et al. (2002) and Andrienko et al. (2003)). Film 4 presents Falcon *weight sliders* which is used for score weight assignment in a collective or individual collaboration. It presents the sliders for Rating method as well as Pairwise Comparison approach where the relative preferences of mutual criteria is defined by the user(s).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.09.042.

The impact of different assigned criteria weights on the final score is depicted in Fig. 15. Increasing the energy yield criterion weight (Fig. 15 (a)) leads to a low score. This is due the low produced power with regard to the total power target. Increasing the number of wind turbines, keeping all other parameters and weights the same (high energy yield criterion weight), results in an increased score (Fig. 15 (b)). By decreasing the energy yield criterion weight and increasing the shadow criterion weight, keeping all other parameters (wind turbine types and configuration) the same as (b), the final score decreases to 89.65 (Fig. 15 (c)). This is due to the combination of high number of affected buildings by shadow and shadow criterion weight.

In each scenario design stage, the total score is presented which can potentially orient the stakeholders towards a more efficient scenario (re)design. The applied decision function can be used together with the knowledge of the local inhabitants as well as the participants' judgements about the turbines visual effects and other impacts (noise, shadow, visibility and power generation), provided through numbers and charts in Falcon interface, to orient towards a decision. The final decision will be taken after multiple iterations through the geodesign steps.

While the previously developed decision support systems have focused on important aspects of wind turbine site selection, the implementation results of Falcon demonstrates the advancement of this system regarding the interactivity, flexibility and multidimensionality which makes it a suitable decision support tool for a wide range of participants. Mari et al. (2011) designed a web-oriented decision support system to help public operators in preliminary determination of proper wind turbine locations. This system provides the information as map layers (comprising wind data, wind power maps, exclusion maps and background layers) which can be overlaid by the users for an easier navigation through the region. While these map layers provide useful information to the user, the incorporation of numerical impact models in Falcon provides the means for an objective evaluation of the different environmental effects of a wind turbine on its surroundings. Aydin et al. (2010) considered different wind turbine environmental impacts in their developed decision support system. These impacts were indicated as the fuzzy objectives of the decision problem which were quantified with different criteria. The applied criteria were the buffer zones defined through Turkish legislations as well as previous studies which were used to define the membership functions of the acceptability fuzzy sets aimed for the final estimation of priority sites. In another study, Ramírez-Rosado et al. (2008) have created different criteria maps for different user groups followed by the creation of tolerance maps using GIS techniques. The resulting tolerance maps of the decision support system are used for the selection of the best locations of wind turbines. While the presentation of the suitable locations of wind turbines through these indicators are useful, the explicit and detailed numerical feedbacks on each environmental impact for each adjusted scenario, as in Falcon, offers a deeper view and can open up a more objective discussion process between the different user groups. Furthermore, the possibility of seamless wind turbine placement and movement, rather than predefined (grid) locations, and real-time update of environmental models in Falcon upon the placement/movement of each wind turbine, rather than offline (pre) calculations, supports a seamless discussion process and makes Falcon a novel decision support system for wind turbine site planning compared to the previously developed tools. The 3D environment, the possibility of straightforward integration of other map layers by the user, without the alteration in the system (provided through open standard web service incorporation in Falcon) and the integration of massive geospatial data (through tiling techniques) which expands the analysis feasibility to the extent of the whole country or more (See Section 3.2) are other privileges of Falcon compared to the previously mentioned tools.

3.2. International context

The choice to make Falcon compliant with geospatial web standards (Section 2.1) enables this application to be effortlessly applied in other countries eliminating data formatting inconsistencies and supporting data interoperability. The system's skeleton, namely the game engine-GIS-analytical models integration, remains unchanged and the alteration merely occurs in the input data. Naturally, the data needs to be present, but recent years have witnessed a burst of governmental and non-governmental data being published and made available online via standardized access mechanisms and often within national or international Spatial Data Infrastructure such as NSDI in the US (Federal Geographic Data Committee, 1995), ASDI in Australia (ANZLIC, 1996), Geosur in south America (van Praag and Borrero, 2012) and INSPIRE in Europe (European Commission, 2007). In the European context, the data Falcon currently uses is in most cases prescribed within INSPIRE initiative meaning European countries are expected to collect and share most of this data in a comprehensive and standardized format. Table 2 presents the required input data for applying Falcon in other countries as well as the OGC standard data access type and the INSPIRE annexes and themes.

4. Conclusions

The involvement of the stakeholders with different, and sometimes contradictory, viewpoints in wind turbine site planning calls for the presentation of clear and easy to use information on the multiple aspects of a wind turbine. This recapitulates the

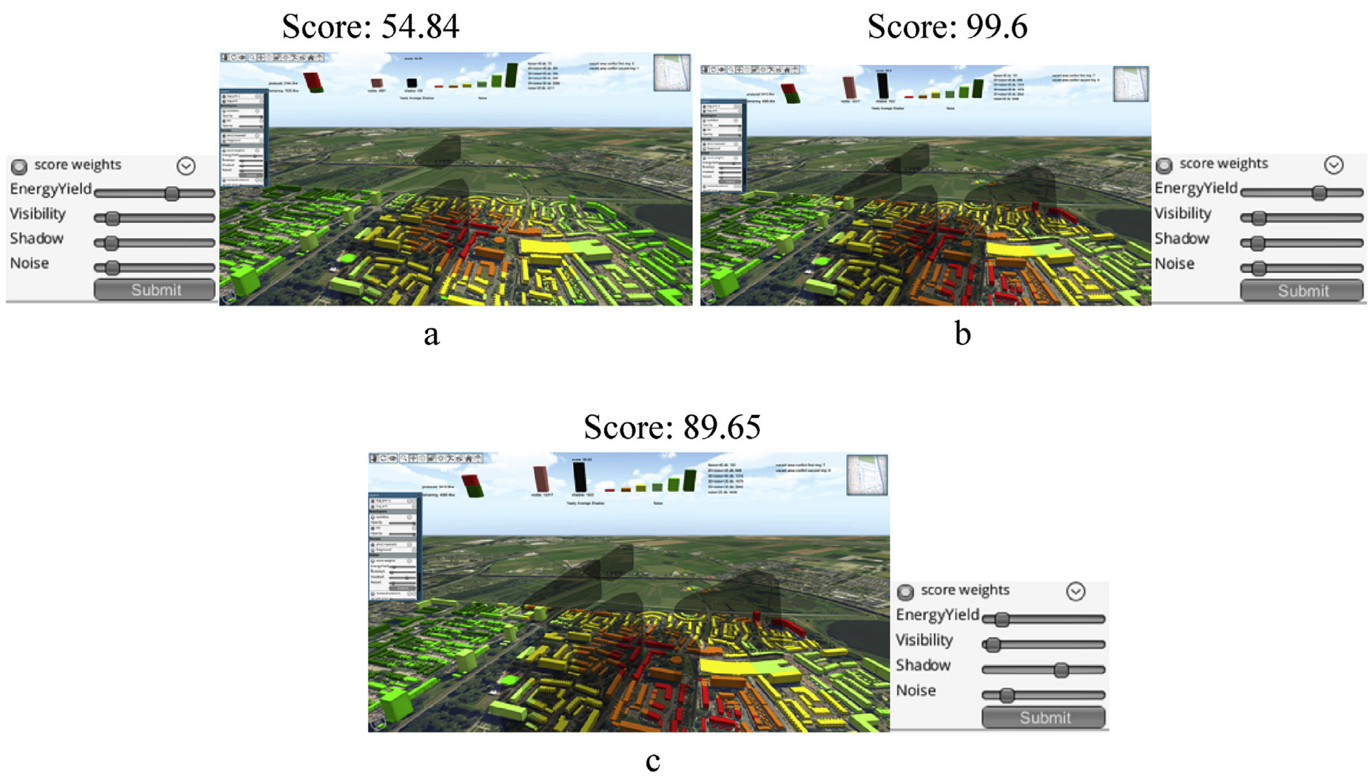

Fig. 15. The impact combination of criteria weight and configuration on the final score; the higher number of wind turbines in (a) compared to (b), in combination with a high energy yield criterion, with all other parameters the same, results in a higher score. The higher shadow criterion weight (and the lower energy yield weight) in (c), with the same wind turbines' configuration as (b), leads to a decreased score.

Table 2
The required input data and the relevant service types for the deployment of Falcon in other countries as well as their equivalent INPIRE annexes and themes (European Commission, 2007).

Input Data	Service Type	INSPIRE Theme	An-nex	comments
Building Address	WFS	Addresses	I	
Building Footprint	WFS	Buildings	III	
Building Height Data	WFS	Elevation	II	in combination with the previous
Aerial Photo	WMS	Orthoimagery	II	
Terrain Height Model	WMS	Elevation	II	
Wind Velocity	WMS	Meteorogical geographical features	III	also energy resources theme
Electricity Demand	WMS		–	
Existing wind Turbine Locations	WFS	energy resources	III	
Restriction Elements	WFS		–	based on local legislation
Vegetation	WFS	Land cover	II	
Landuse	WMS	Land use	III	
Humidity	WMS	Meteorogical geographical features	III	

importance of having a system in the process that embeds the information regarding the different attributes involved in a wind turbine planning. In line with this, we have developed an interactive multidisciplinary wind turbine planning platform. It enables a geodesign approach, which supports a design attitude of drawing, (immediate) evaluating and redrawing (Albert and Vargas-Moreno, 2012). The adaptation of the geodesign framework in the system enabled the structuring of the multidisciplinary process where the design and impacts are clearly intertwined and linked. In this platform, we have integrated game engine, GIS and different analytical models for real-time environmental analyses regarding wind turbines siting in the Netherlands.

The implementation of raster and 2D/3D vector tiling techniques in the system was a solution for data volume issues, through which different 2D/3D geospatial datasets of the whole of the Netherlands could be loaded on-the-fly in the game engine based platform. Through the incorporation of OGC standard protocols and web services in our system, many diverse datasets from different resources can be loaded to Falcon. This can untangle the data accessibility knot, which is mentioned as an impediment for the widespread application of a planning support system (Vonk et al., 2005). Furthermore, these datasets are interoperable and can be used directly, since the data formatting is no longer an issue.

Receiving real-time feedbacks at each design phase is considered an ideal geodesign instance (Flaxman, 2010). By integrating different analytical models in our system, the participants receive feedback of the different environmental impacts continuously during scenario design and with every adjustment. The long processing time required for running a such models is often a problematic issue. While in an offline system, this might be less a problem (e.g. commissioned environmental impact reports), in a live design procedure, where the participants should receive quick responses and real-time feedback of the design impact, the processing time plays a crucial role. To overcome this issue, we have applied different game engine functionalities (e.g. physical simulations through the game engine's physics engine) and GIS techniques for the real-time performance of the impact models.

Such a real-time impact analysis can inform the participants of the influence of their alteration each time a change model is proposed, during the design process rather than a final indication after the completion of the whole scenario design. This instantaneous impact assessments provides a seamless exploration scope and an intertwined discussion process.

The integration of the whole geodesign models, processes and impact evaluations into one platform, which is understandable for participants from different domains is mentioned as a privilege for a geodesign process (Albert and Vargas-Moreno, 2012). Such a unified platform splices the design process and omits the dependency for external software. The public accessibility of this platform through internet offers an easier way for public participation in planning processes (Batty, 1998; George, 1997; Albert and Vargas-Moreno, 2012).

We believe that this 3D game engine-based and GIS integrated platform has great value in a participatory planning process and can be applied in wind turbines site selection. However, the usability and participants' experience of this tool should still be assessed in an applied geodesign workout.

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